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Review article

Adaptation of solar energy in the Global South: Prospects, challenges and opportunities

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ABSTRACT

The Global South comprising economically disadvantaged regions of the world face various challenges such as limited access to electricity, clean water, industrialization, and food security. Solar energy, as a sustainable and abundant resource, holds great potential to address these challenges. Despite its immense potential, the Global South encounters hurdles related to technology adoption, infrastructure, and financial constraints. This review examines the history, classifications, global statistics, merits, and demerits of solar technology in the Global South. Furthermore, it delves into various applications of solar energy, including extreme environments, residential electricity generation, transportation, and industrial usage in this region. This study concludes by providing new insighths and highlighting the significant role solar energy can play in shaping the future of the Global South if challenges are adequately addressed, and opportunities are embraced.

1. Introduction

Solar energy has attracted significant attention as a prospective remedy for the multifaceted energy and development predicaments confronting the regions encompassed by the term "Global South" [1–3]. This geographical classification comprises nations and territories grappling with varying degrees of economic inequality, manifesting in a host of challenges including but not limited to restricted access to fundamental services, impediments to industrial advancement, and uncertainties related to food provision [4–6]. This study seeks to explore the capacity of solar energy to assuage these obstacles while simultaneously scrutinizing the barriers and opportunities entwined within its integration.

The Global South is emblematic of a dichotomous landscape, where towering economic disparities coexist with persistent struggles against inadequacies in fundamental infrastructure [7–9]. This dichotomy materializes as a complex interplay of challenges encompassing diverse sectors of societal development. Predominant among these are the formidable difficulties in securing reliable and affordable sources of energy, a prerequisite for not only bolstering industries but also for providing equitable living standards [10,11]. Solar energy, as a renewable and abundant resource, offers a beacon of hope in these milieus of challenges. The premise of harnessing

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the sun's radiative potential to generate clean and sustainable power holds promise to address a spectrum of developmental disparities that persist in the Global South. However, the magnitude of this promise necessitates an exploration that goes beyond the veneer of optimism, delving into the intricacies of its feasibility, efficacy, and compatibility with the specific contours of challenges endemic to the Global South [12–16].

Considering this, the main purpose of this paper is divided into two-folds. First, it seeks to assess the potential of solar energy as a viable remedy for the range of challenges prevalent in the Global South. From diminishing the energy access gap to augmenting industrialization efforts and reinforcing food security initiatives, the spectrum of applications is wide-ranging. Secondly, this paper explores the journey to harness solar energy as a catalyst for development with its challenges. These include technological barriers, infrastructural constraints, financial impediments, and socio-cultural considerations that warrant a comprehensive understanding. The subsequent sections of this paper present an in-depth exploration of solar technology, its various applications, specific challenges and opportunities it presents in the context of the Global South. By scrutinizing both the theoretical promises and the practical impediments, this study aims to contribute to a nuanced understanding of solar energy's potential and limitations in reshaping the trajectory of development in economically disadvantaged regions. This work further explores the realm of potential solutions, scrutinizing the multifaceted dimensions of solar energy's application, the challenges it encounters, and the opportunities it engenders. Finally, insights that could catalyze innovative strategies to bridge the gaps that persist in the Global South's pursuit of equitable and sustainable development are presented.

2. The Global South

The Global South is a diverse group of nations and territories that share a common thread of economic disparity compared to their counterparts in the Global North [17]. It comprises Latin America, Africa, Asia, and Oceania as shown in Fig. 1.

This classification serves as a guide for regions facing distinctive developmental challenges, such as the lack of basic ammenities, limitations in fostering sustainable industrialization, and food security concerns [19,20]. The Global South faces significant economic inequality, with inadequate electricity access hindering progress across various sectors. This limits educational opportunities and hampers healthcare provisions [21,22].

Industrialization in the Global South is notably slow compared to its counterparts in the Global North, impeded by infrastructural bottlenecks, technological limitations, as well as insufficient investment in research and development [23,24]. This impedes job creation, resilient supply chains, and value-added production expansion. Food insecurity is a significant issue in many regions, due to limited access to food resources, climate change, unpredictable weather patterns, and inadequacies in agricultural practices [25]. However, this classification is not a condemnation of potential, but a call for innovative solutions that align with the specific contours of the developmental landscape. Solar energy offers a potential solution to addressing these challenges by transcending traditional energy systems, providing clean water solutions, fostering sustainable industrialization, and enhancing food security (Fang et al., 2020; [26]).

Less than 0.1% of the global south's area shown in Fig. 2 could afford enough solar panels to supply all of its electricity demands. Solar energy can be a transformative force capable of surmounting these challenges, offering a blueprint for sustainable development that resonates with the unique dynamics of the Global South.

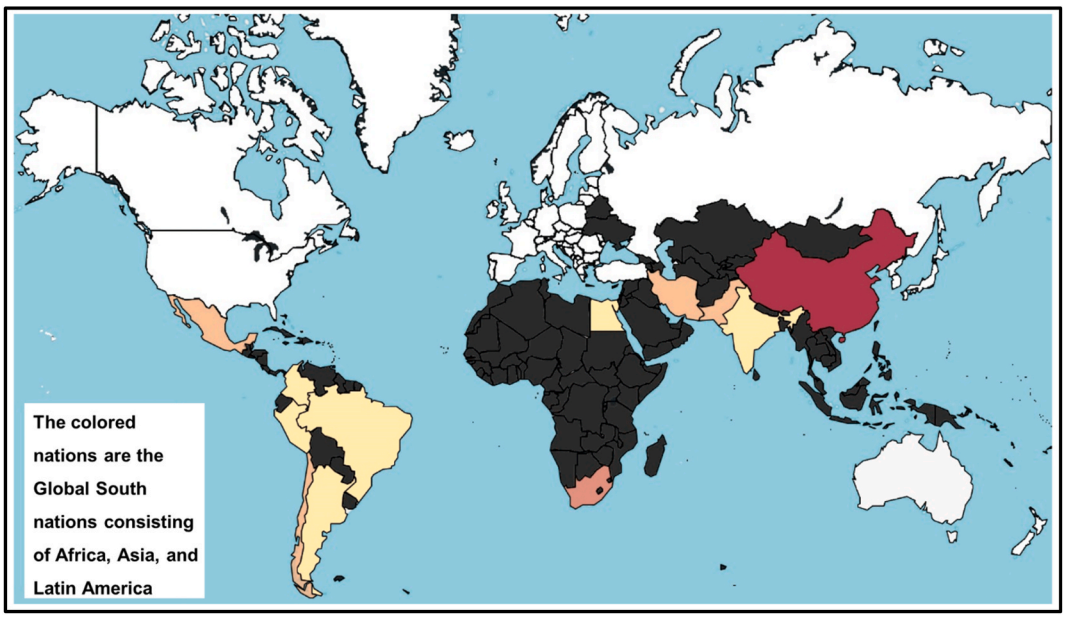


Fig. 1. Global South countries (Group of 77 countries and China) [18].

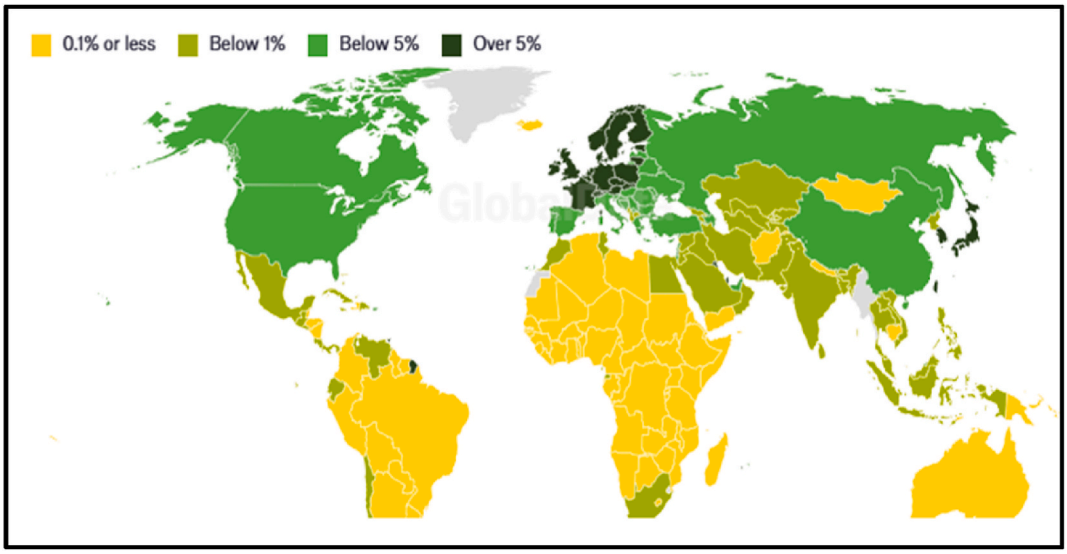


Fig. 2. Share of land required to generate all energy from Solar (Energy Monitor, 2021).

2.1. 2.1 key challenges of the Global South

Countries in the Global South share similar challenges. These set of challenges have hindered the development of the regions. They are mainly centered around electricity, water, food, and related challenges.

2.1.1. Electricity

Inadequate access to electricity in the Global South hinders economic progress and human development [27,28]. Energy issues or the lack of access to modern energy services is a significant problem in many regions, with vast populations lacking the benefits of electrification. This dearth has profound socio-economic and human developmental implications. Economic stagnation and human deprivation are also exacerbated by access to adequate electricity. As industries struggle to operate optimally, small and medium-sized enterprises face challenges in thriving, and many resort to expensive and environmentally harmful alternatives. Education and healthcare services are also significantly hampered in regions lacking reliable electricity, with schools unable to offer modern teaching tools and healthcare facilities limited in providing essential medical services [29].

Solar energy offers a transformative solution to address these challenges [30]. Solar photovoltaic (PV) systems convert sunlight directly into electricity, offering a decentralized approach that aligns with the needs of areas without conventional energy access. Solar technology is modular and scalable, thereby allowing for tailored solutions that align with local needs and capacities. Communities in the Global South can take charge of their energy future by installing solar panels on rooftops and establishing microgrids to connect households, ensuring a steady supply of electricity. This not only spurs economic activities but also engenders a sense of empowerment within local communities, as they become active participants in their development [31–33].

The adoption of solar energy can change farm households' production operations by providing a consistent source of electricity, similar to the shift from animal to tractor power. With the use of contemporary equipment like electric pumps and processing tools, this shift increases production by promoting output and efficiency. Labor demands are decreased by solar-powered equipment, freeing up labor for higher-value jobs or non-farm options. Scale economies—larger irrigation systems or enlarged processing facilities, for example—are made possible by access to dependable electricity, which lowers average costs and increases competitiveness. Electricity also makes value-added processes like food processing possible, which improves the quality and marketability of products. Takeshima [34], for instance, illustrates this when tractor power replaces animal power. Furthermore, the durability of solar power reduces susceptibility to fuel price variations or system outages, allowing for efficient adaptability to changing circumstances. Solar-powered agriculture makes a substantial contribution to the enhancement of market access, reduction of poverty in the Global South, productivity gains, labor savings, enabling scale economies, and resilience building. The availability of abundant sunlight in most of the countries in the Global South offers rays of hope for the electrification of this region using solar energy [35]. Despite the avalanche of sunlight, most countries in the Global South are not tapping into the technology of solar. This is due to several factors including the high cost of importing solar panels from other countries.

Nevertheless, taking into account the common power producing capacity, it is necessary to investigate the kinds of electricity needs for which solar power may be more appropriate. In rural or off-grid locations where extending standard grid infrastructure is either impracticable or excessively expensive, solar power is especially well-suited for supplying electricity. Solar energy can be used in these places to power small appliances, light up homes, and meet basic electricity needs through stand-alone systems such mini-grids, microgrids, or solar home systems. Residential electricity needs are frequently met by solar power, particularly in areas with plenty of sunshine and encouraging laws or incentives. Rooftop solar photovoltaic (PV) systems can produce power for domestic use on their

own, minimizing utility costs and dependency on the grid. The average size of a residential solar system is usually determined by the amount of electricity required by the household, which includes lighting, appliances, and gadgets. Even so, in some parts of Africa, such as Nigeria, some households still have difficulty using electric presses for ironing clothes, pumping water, and other high-energy machines that are not powered by solar energy. The emergence of deep freezers and electric pressing irons that work with solar power is a result of modern advancement. Wealthier households have been able to power heavy and high-power-consuming devices by investing in more solar panels and batteries. In rural locations with limited access to diesel fuel or grid electricity, solar-powered water pumping systems are commonly utilized for agricultural irrigation. Water from wells, rivers, or boreholes can be effectively raised by solar pumps for crop irrigation, offering a dependable and sustainable source of water for agricultural practices. For the purpose of supplying electricity for telecommunications infrastructure, such as base stations, internet connectivity devices, and mobile phone towers, solar power is essential. Telecom towers powered by solar energy provide continuous communication services in underserved or distant areas where grid electricity is unavailable or unstable. Community buildings like schools, clinics, community centers, and places of worship are ideal candidates for solar energy use. The potential of solar photovoltaic (PV) systems to supply dependable electricity for a range of uses, from small-scale to industrial settings, is becoming more widely acknowledged. A thorough analysis of DC-DC converter topologies and modulation techniques, which are crucial elements in solar PV applications, is given by Raghavendra et al. [36]. For researchers and designers working in the subject of solar PV applications, this work is an invaluable resource. In addition, Choi et al. [37] propose a four-step process that includes system design, modeling, economic feasibility evaluation, and solar site assessment in order to evaluate the potential of floating PV systems. This process is essential to comprehending the real-world application of solar PV systems. Furthermore, Mahmud & Blanchard's [38] study identifies factors that characterize solar photovoltaic systems' dependability, highlighting the need of system performance analysis in guaranteeing a steady supply of electricity.

Furthermore, through sustainable energy practices, solar power has been shown to lower operating costs, offset grid electricity use, and demonstrate corporate social responsibility. According to Kassem et al. [39], PVGIS is a trustworthy software program for modeling solar PV systems, which is necessary for determining the feasibility and possible advantages of adopting solar energy. Moreover, Guzmán et al. [40] stress the importance of PV system sizing technique, taking into account the coupling of electric load and solar energy potential, which is critical for optimizing the performance and design of solar PV installations.

Research on solar lanterns has brought attention to the advantages and disadvantages of offering sustainable lighting options, influencing conversations about rural electrification and access to renewable energy sources. Grimm et al. [41] looked at how solar lantern distribution programs affected rural communities, highlighting how they may help people have better access to energy and support themselves. The study covered how solar lanterns, especially in off-grid populations that have restricted chances of getting electricity, might improve safety, productivity, and education. But issues like cost, upkeep, and user preferences were also noted, highlighting the necessity of all-encompassing strategies to remove adoption hurdles and guarantee long-term viability. The technical performance and user satisfaction of solar lanterns were studied by Stojanovski et al. [42], with particular attention paid to battery life, brightness, and durability. The study made clear how crucial product quality and dependability are in influencing customer acceptance and happiness. Cost effectiveness, distribution routes, and cultural aspects were also found to be important variables to take into account for the effective installation and adoption of solar lanterns in rural areas. These studies bring insightful information to the debates surrounding solar lanterns, highlighting both the possible advantages and the issues that must be resolved to fully realize their promise to improve rural development and energy access. Policymakers, practitioners, and researchers can work toward developing sustainable and inclusive energy solutions for marginalized populations by addressing technical, economic, and social elements. Solar electricity has been found to provide advantages in the industrial environment for a number of industries, including manufacturing, food processing, hospitality, and retail. Furthermore, solar PV systems have been acknowledged for their contribution to emergency and disaster relief operations, offering a dependable electricity supply in the event of power outages or natural disasters. The work of Mayanjo & Justo [43] provides support for these findings as they address the development of solar PV systems for mini-grid applications. Their study highlights the potential of solar energy to support community development projects and important services. The studies support the idea that solar PV systems can provide dependable electricity for lighting, fans, computers, refrigeration, and other essential services, thereby improving the quality of life and assisting community development initiatives. The studies also offer insightful information about the technical aspects, economic factors, and practical applications of solar PV systems.

Due to its versatility, solar power may be used to cover a wide range of electrical needs in a variety of sectors and applications. Its widespread acceptance is fueled by its scalability, dependability, and sustainability, which make it a desirable alternative for off-grid and grid-connected environments. However, some tasks that need a lot of material movement, like pumping or operating small tractors, may still require the use of traditional energy sources like diesel or non-solar electricity supplied by the grid. Although the accuracy of these activity category classifications may be questionable, the key issue is whether or not solar technology-suitable activities are limited to those with comparatively lower power requirements.

2.1.2. Water

Access to clean water is one of the United Nation's sustainable development goals and a prerequisite for a dignified and healthy life. However, in many parts of the Global South, the scarcity of clean water is a significant issue, impacting public health, sanitation, and overall quality of life. Access to clean water is crucial for sustenance and public health, as it leads to waterborne diseases and exacerbates the burden on healthcare systems [44,45]. Solar energy offers innovative solutions to tackle clean water scarcity by harnessing the sun's energy to treat contaminated water, making it safe for consumption and domestic use. Solar-powered water purification systems harness the sun's energy to power pumps, filtration processes, and disinfection methods, purifying water without relying on traditional energy grids.

One of the advantages of solar-powered water purification is its decentralization, empowering local communities to take charge of

their water supply without relying on extensive and often unattainable centralized infrastructure. This is especially crucial in remote areas where traditional methods of water treatment are unfeasible. Solar-powered water purification is environmentally sustainable, reducing reliance on fossil fuels and making them adaptable and effective across diverse settings [46–49]. By harnessing solar energy for water purification, communities gain access to a continuous and reliable source of clean water, addressing immediate health concerns and empowering individuals, particularly women and children, who often bear the brunt of water collection responsibilities.

The potential for solar energy use in the Global South makes the adoption of solar applications there a matter of growing attention. Research has shown that the Global South has a significant potential for solar energy adoption, especially in areas like Saudi Arabia and Northern Nigeria where statistical analyses have shown that solar energy adoption is feasible [50,51]. However, in places like South Africa, adoption challenges have been noted, including cost concerns and a shortage of experienced labor for solar power plant construction and maintenance [52]. There is also an increasing interest in sustainable electrification techniques for these communities, as evidenced by studies done to examine the feasibility of solar nano-grids as a way to address energy needs in rural areas in the Global South [53].

Off-grid solar solutions have experienced significant growth in the Global South, particularly in sub-Saharan Africa and Bangladesh. The International Energy Agency [54] reported a substantial increase in off-grid solar capacity in sub-Saharan Africa from 30 MW in 2012 to over 1100 MW in 2019 [55]. This growth is attributed to the rising popularity of solar home systems, exemplified by Bangladesh's Solar Home System (SHS) program, which has installed over 6 million solar home systems, benefiting millions of people. Also, Hossain et al. [56] did a feasibility of solar pump for sustainable irrigation in Bangladesh. Additionally, solar-powered water pumps are being widely adopted in agriculture, with over 300,000 installations globally by 2017, a significant portion of which are in the Global South. Community-based solar projects and solar microgrids are also emerging as viable solutions, providing electricity to communities not connected to the grid or facing frequent power outages. Furthermore, many governments in the Global South are implementing policies and programs to promote solar energy adoption, including incentives such as subsidies, tax breaks, and feed-in tariffs, while the private sector is increasingly investing in solar projects, driving innovation, reducing costs, and expanding access to solar energy solutions.

The adoption of solar applications in the Global South is growing rapidly, driven by factors such as declining costs, technological advancements, supportive policies, and increasing awareness of the benefits of solar energy. There are some success stories of solar applications that are already happening within the Global South that may be more viable in other Global South. For example, Kishore et al [57] examined the adoption and impact of solar irrigation pumps among farmers in Rajasthan, India, as well as the state policy surrounding these technologies. The article discusses the introduction of solar irrigation pumps as an alternative to diesel or grid-based pumps for agricultural water pumping. These solar pumps are seen as a sustainable and environmentally friendly solution, particularly in regions with abundant sunlight like Rajasthan. The authors explore the experiences of farmers who have adopted solar irrigation pumps. They find that many farmers have embraced solar technology due to its reliability, cost-effectiveness, and environmental benefits. Solar pumps offer a more predictable source of power compared to erratic grid electricity or expensive diesel. The article discusses the impact of solar irrigation pumps on agricultural productivity and income generation. Solar pumps enable farmers to irrigate their fields more efficiently, leading to increased crop yields and income. Additionally, solar pumps reduce the reliance on diesel, resulting in cost savings for farmers. Despite the benefits, the authors identify several challenges and constraints associated with the adoption of solar irrigation pumps. These include high upfront costs, limited access to financing, technical issues, and inadequate maintenance services. Addressing these challenges is crucial for the widespread adoption of solar pumps. The article examines the role of state policy in promoting the adoption of solar irrigation pumps. In Rajasthan, the government has implemented various policies and incentives to encourage the use of solar energy in agriculture, including subsidies, loan schemes, and net metering arrangements. However, the authors suggest that more comprehensive policies are needed to address the barriers to adoption effectively. Based on their findings, the authors propose several recommendations to enhance the uptake of solar irrigation pumps. These include improving access to finance, providing technical support and training to farmers, strengthening maintenance services, and promoting awareness and capacity-building initiatives. Overall, the article highlights the potential of solar irrigation pumps to transform agriculture in regions like Rajasthan, offering sustainable and reliable energy solutions for farmers. However, addressing the challenges and leveraging supportive state policies are essential for realizing the full benefits of solar technology in agriculture.

2.1.3. Industrialization

Industrialization is crucial for economic progress, job creation, and improved living standards. However, limited industrial growth in the Global South presents a significant challenge, hindering economic advancement and limiting sustainable development. Solar energy can help address these challenges by providing a reliable, sustainable, and decentralized energy source. Industrial growth in the Global South is hindered by limited access to reliable energy sources, which can lead to erratic production cycles and operational inefficiencies. Thus, combined with scarcity of financial resources and inadequate technological infrastructure, creates a challenging environment for industries to thrive.

Limited industrialization stifles economic diversification and job creation, particularly among youth. Informal sectors proliferate due to the lack of formal industrial enterprises, perpetuating cycles of poverty and underemployment [58–60]. Solar energy can be a catalyst for industrial transformation in the Global South by offering a reliable and sustainable energy source, addressing the limitations of traditional power grids, and enhancing productivity and operational stability. Solar panels can be deployed on-site, providing a consistent source of power that reduces dependence on unreliable energy grids. The modularity of solar technology allows for tailored and localized solutions, enabling flexible growth trajectories and eliminating the need for extensive grid expansion. By embracing solar energy, the Global South can pave the way for inclusive and sustainable industrialization, fostering job creation and economic diversification [61].

2.1.4. Food

Food security is crucial for human well-being, health, productivity, and overall quality of life. However, insufficient food production and distribution systems in the Global South lead to widespread food insecurity and malnutrition. This issue impacts human development, children's growth, and cognitive development, and perpetuates cycles of poverty [62]. Solar energy offers innovative solutions to strengthen and nourish agricultural systems [63,64], mitigating the impact of traditional energy constraints on farming practices and fostering sustainable and resilient food production. Solar-powered agricultural technologies provide practical applications in various aspects of agricultural operations such as irrigation systems, cold storage facilities, and mechanization.

Hashing solar energy empowers farmers to confront food insecurity head-on, bolstering agricultural resilience and ensuring the long-term viability of food systems. Solar-powered agricultural solutions align with sustainable farming principles, minimizing the ecological footprint and ensuring the long-term viability of food systems [65,66]. Solar energy can transform the issue of food security in the Global South by redefining agricultural landscapes, fostering sustainable practices, and strengthening food systems against climate change and energy limitations.

The reliance on the agrifood sector in the Global South is significant, with agriculture playing a crucial role in the economies and livelihoods of many countries. In recent years, solar technologies have emerged as valuable tools for enhancing various aspects of agricultural production, processing, and post-harvest management. Solar-powered water pumping systems are increasingly used for irrigation in agriculture, particularly in regions where access to grid electricity or diesel fuel is limited or costly. Solar irrigation pumps utilize photovoltaic panels to generate electricity, which powers water pumps to lift water from wells, rivers, or reservoirs for crop irrigation. This technology helps improve water efficiency, reduce reliance on fossil fuels, and enhance agricultural productivity, especially in areas prone to water scarcity. Solar dryers are utilized for drying agricultural products such as grains, fruits, vegetables, herbs, and spices. These systems harness solar energy to create optimal drying conditions, allowing farmers to preserve and process their harvest efficiently. Solar dryers can be designed as passive or active systems, utilizing direct or indirect solar radiation to remove moisture from agricultural produce. By reducing post-harvest losses and improving product quality, solar drying technologies contribute to food security, income generation, and value addition in the agrifood sector. Solar cooling technologies, such as solar-powered refrigeration and cold storage systems, are crucial for preserving perishable agricultural products, including fruits, vegetables, dairy, and meat. These systems utilize solar energy to drive absorption or compression refrigeration cycles, maintaining low temperatures to extend the shelf life of agricultural produce. Solar-powered cold storage facilities enable farmers and food processors to store and market their products effectively, reducing spoilage and improving market access.

In coastal or arid regions where freshwater resources are scarce, solar desalination technologies offer a sustainable solution for agricultural irrigation. Solar desalination systems utilize solar energy to evaporate seawater or brackish water, condensing it into freshwater for irrigation purposes. By harnessing abundant sunlight and leveraging renewable energy sources, solar desalination enhances water availability and resilience in agricultural systems, supporting crop cultivation in water-stressed environments. Solar energy is increasingly integrated into agro-processing equipment, such as mills, crushers, grinders, and oil presses, to mechanize and optimize processing operations. Solar-powered agro-processing technologies help streamline production processes, increase efficiency, and reduce labor requirements, benefiting smallholder farmers and rural communities. By providing reliable and sustainable energy solutions, solar technologies contribute to value addition, income diversification, and rural development in the agrifood sector.

Solar drying technologies utilize solar energy to remove moisture from agricultural products, enhancing their shelf life and reducing post-harvest losses. Solar dryers, as highlighted by IRENA [67], come in various designs, including direct, indirect, and mixed-mode systems, tailored to specific crops and climatic conditions. Solar pumping for irrigation involves using solar-powered water pumps to lift water from wells or other sources for agricultural irrigation, providing a sustainable and cost-effective solution, especially in off-grid areas. Additionally, solar technologies are employed in the drying of salt, utilizing solar heat to evaporate water from saltwater ponds, yielding salt for various industrial and culinary applications.

Solar drying technologies have garnered attention in the Global South for their potential to mitigate post-harvest losses and enhance food security [68]. Implemented by various organizations, pilot projects and case studies demonstrate the benefits of solar dryers, including decreased losses, improved product quality, and augmented income for smallholder farmers. Recognized as an efficient method, solar drying utilizes abundant solar radiation in tropical regions, offering a cost-effective solution for preserving a wide array of agricultural products [69]. Highlighted as a preferred food processing technology, solar drying has been shown to reduce post-harvest losses, particularly when conducted in enclosed structures [70]. Emphasized for their role in a low-carbon future, solar drying technologies have spurred research into large-scale industrial applications and safe drying procedures [71]. Studies have evaluated their technical performance and impact on nutritional quality, underscoring the importance of well-designed technology for ensuring product quality [72]. Additionally, the importance of safe solar drying procedures has been underscored to increase consumer acceptability of solar-dried products, as evidenced by the need for safe solar drying procedures to enhance consumer acceptability of solar-dried tomato products in Ghana [73]. Solar drying technologies present a promising and sustainable solution for preserving agricultural products in the Global South, urging further research and development in this field [74].

Solar technologies offer diverse opportunities to enhance agricultural sustainability, resilience, and productivity in the Global South. By harnessing solar energy for irrigation, drying, cooling, desalination, and agro-processing applications, farmers and food producers can overcome energy challenges, mitigate climate risks, and improve livelihoods across the agrifood value chain [75]. Continued research, investment, and policy support are essential to promote the widespread adoption and integration of solar technologies in agriculture, fostering sustainable development and food security in the Global South.

3. Solar technology

Solar technology, also known as solar energy, is a suite of mechanisms and innovations that harness the radiant energy emitted by the sun and convert it into useable power [76,77]. Solar power is the cheapest form of electricity globally, with prices plummeting 82% between 2010 and 2019, and being cheaper than fossil fuels in over 60% of the world [78]. Its roots can be traced back to ancient civilizations, with structures designed to capture and magnify sunlight for heating purposes during colder months. The 19th century saw the development of solar photovoltaic (PV) technology, which uses semiconductor materials to convert sunlight into electricity through the photoelectric effect [79–82]. The 20th century saw significant advancements in solar technology, particularly driven by space exploration efforts.

Solar power is the process of turning solar energy directly into electricity using photovoltaics or indirectly through concentrated solar power [83]. The PV effect is used by PV cells to transform light into an electric current [84]. Solar Energy is a form of renewable energy that converts sun energy into electricity. It uses a solar panel to trap the energy from the sun to generate electricity. The solar panel converts energy from the sun to electricity. The key types of solar panels are monocrystalline, polycrystalline, and thin film solar panels [85] as shown in Fig. 3.

The key components of a solar system include a solar panel, which captures sunlight and converts it into electricity, a charge controller that regulates the flow of energy from the solar panel to the battery, a battery that stores the generated electricity for later use, an inverter that converts the stored DC power into AC power for household appliances, wires that connect the various components, and of course, the sun, which serves as the ultimate source of energy. Together, these components form a sustainable and renewable energy system that harnesses solar power to provide clean electricity for a variety of applications. The key components of a solar system include a solar panel, charge controller, battery, inverter, wire, and the sun (solar simulator) as shown in Fig. 4.

The working of solar energy is shown in Fig. 5. The sunlight falls on a solar panel which generates electricity through the process of knocking electrons. A charge controller is used for charge control. The generated electricity is stored in a battery for usage. The direct current (D.C) electricity from the battery can be used for home usage or inverted using an inverter to alternating current (A.C).

Solar technology is classified as hybrid, grid-connected, solar operating night and day, and stand-alone. They are further subdivided as shown in Fig. 6.

Solar panels were integrated into satellites, powering critical instruments in the vacuum of space. This galvanized research and development in the solar industry, leading to the refinement of materials and methodologies. The late 20th and early 21st century witnessed a remarkable transformation in solar technology, driven by environmental concerns and technological innovation as shown in Fig. 7.

Solar energy transitioned from a niche application to a mainstream energy source, with improved efficiency and decreased costs, and governments incentivized the adoption of solar power through policy measures and financial support [86,87].

Contemporary solar technology is a testament to human ingenuity and engineering prowess, with solar panels often composed of photovoltaic cells made from materials like silicon. Thin-film solar cells, concentrating solar power systems, and advancements in energy storage technologies have expanded the horizons of solar energy applications. Solar technology has evolved over millennia, from ancient civilizations' solar architecture to the state-of-the-art solar panels on rooftops and powering entire communities today, as shown in Fig. 8. This journey reflects the human capacity to innovate and harness the abundant resources nature provides. Understanding this trajectory is essential for appreciating the transformative potential of solar technology in addressing energy and developmental challenges.

Solar technology is divided into two main categories: solar photovoltaic (PV) systems and solar thermal systems [88,89]. PV systems convert sunlight into electricity through the photoelectric effect, ranging from small rooftop installations to large solar farms. They have diverse applications beyond electricity generation, such as powering calculators and spacecraft, providing energy in remote locations, and offering off-grid solutions. Solar thermal systems capture solar energy in the form of heat, converting sunlight into thermal energy for heating or electricity generation. They can provide domestic hot water, reduce energy consumption in industrial processes, and contribute to space heating in buildings. Both PV and thermal systems can be combined to offer comprehensive energy solutions, enhancing efficiency and addressing the challenges faced by the Global South. Understanding these classifications is crucial for evaluating the potential of solar technology in addressing these challenges.



Fig. 3. Monocrystalline, polycrystalline, and thin film solar panels.

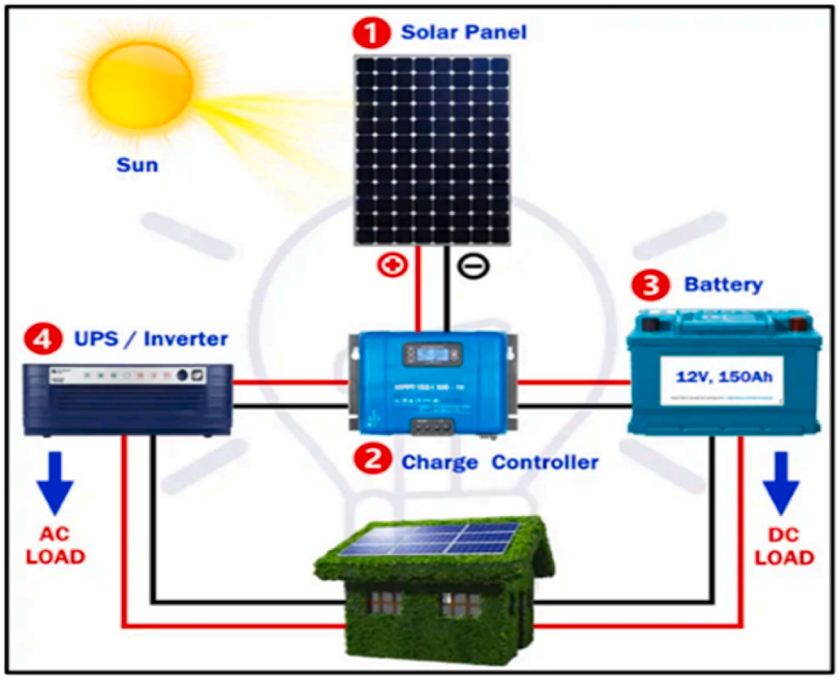


Fig. 4. The main components of a solar panel system.

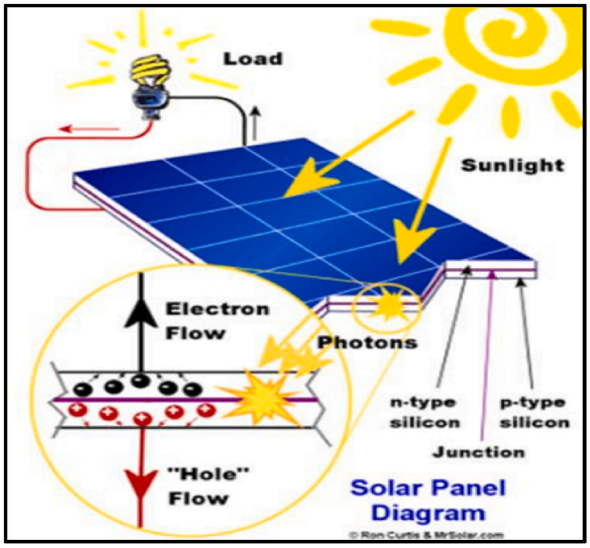


Fig. 5. A picture of the working operation of solar energy.

Solar energy has become a significant player in the global energy landscape, with its rapid growth and substantial contributions to the energy mix demonstrating its transformative potential The vast importance of solar energy is shown in Fig. 9.

The solar revolution has seen a surge in solar capacity, from residential rooftops to expansive solar farms, harnessing the sun's energy to power economies and communities worldwide. This embrace of clean and renewable power aligns with the imperatives of mitigating climate change and reducing carbon emissions. Solar energy's contribution to the global energy mix is significant, with solar capacity constituting a substantial share of total renewable energy capacity [90]. Solar energy's environmental benefits include reduced reliance on fossil fuels, air pollution mitigation, and reduced greenhouse gas emissions. This contributes to the preservation of ecosystems, the reduction of health-related issues, and the future generations safeguarded against climate change. Solar technology also empowers individuals and regions, allowing them to control their energy future and enhance energy security. Decentralized solar installations can continue to provide power during grid disruptions or natural disasters. Understanding these global statistics is crucial

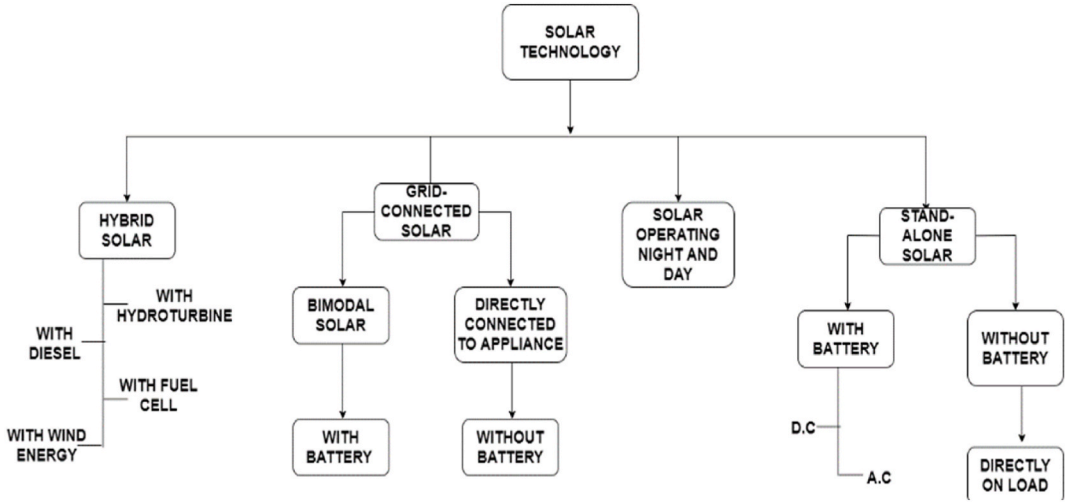


Fig. 6. Classification of solar technology.

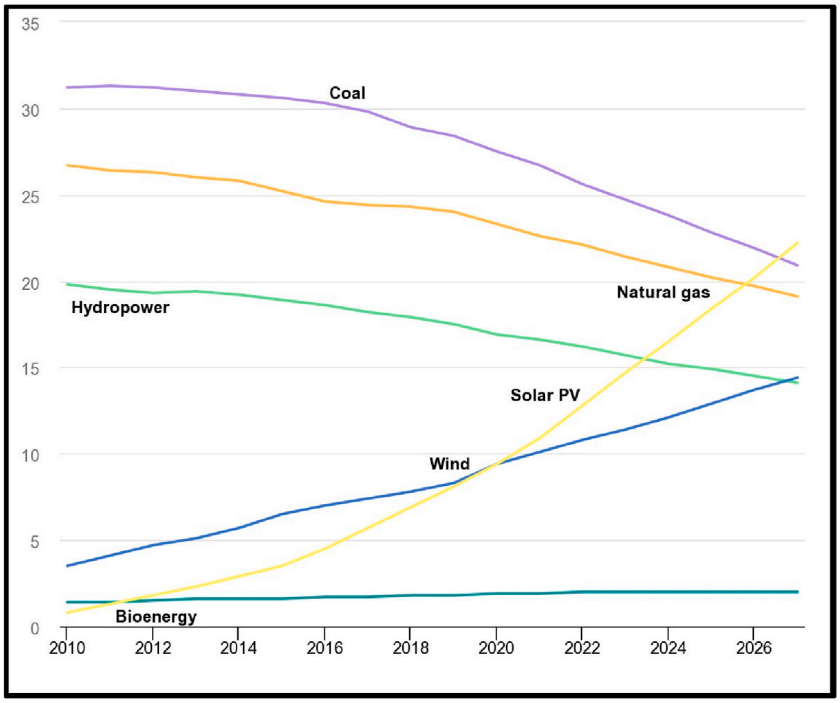


Fig. 7. Cumulative power capacity by technology, 2010–2027 (IEA, 2022).

in evaluating the potential of solar technology to illuminate pathways toward development and progress, particularly in the Global South regions grappling with challenges [91–94].

Solar energy offers numerous benefits across environmental, economic, and societal domains. It is renewable and inexhaustible, ensuring continuity and a sustainable energy future. Solar energy reduces greenhouse gas emissions and fosters cleaner air quality and ecosystems. It also contributes to energy security by diversifying a nation's energy portfolios leading to the reduced dependence on imported fossil fuels. Solar energy systems have low operating and maintenance costs, resulting in predictable and stable energy costs over the long term. Solar energy infrastructure also fosters job creation and economic growth, providing employment opportunities in manufacturing, installation, maintenance, and research. Technological innovation has led to increased efficiency, reduced costs, and improved energy storage solutions, making solar technology accessible to a broader demographic, including rural and underserved communities [95,96]. These merits hold profound implications for regions facing developmental challenges, offering a solution to energy deficits and a catalyst for comprehensive growth and resilience.

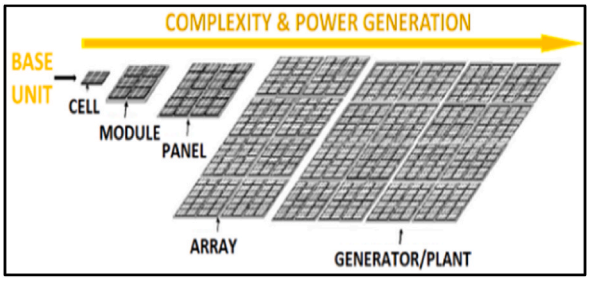


Fig. 8. Different photovoltaic architectures [82].

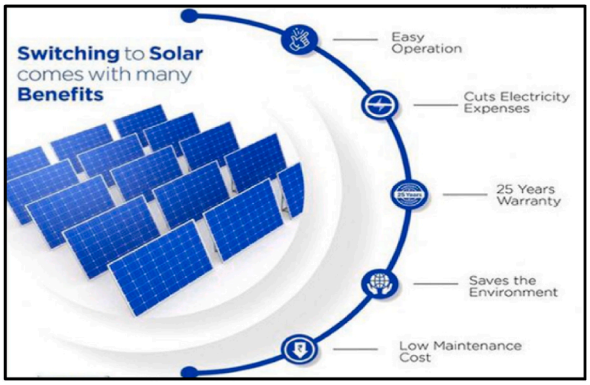


Fig. 9. The importance of Solar energy.

Solar energy holds great potential but faces several challenges, including intermittent high upfront costs, and land requirements. Solar power generation is influenced by sunlight availability, which can vary based on location, time of day, and weather conditions. This variability can lead to inconsistent power supply, especially during periods of reduced sunlight. The initial capital investment for solar systems can be a significant barrier, especially in regions with limited financing options. Balancing land and space requirements is also a challenge, as solar projects often compete with other land uses. Energy storage is essential to mitigate intermittency and ensure reliable power supply [97,98]. The manufacturing and disposal of solar panels can have an environmental impact - extraction of raw materials, energy-intensive production processes, and waste management concerns.

Solar technology adoption faces numerous challenges, including technological, infrastructural, and financial constraints. Technological challenges include improving the efficiency and performance of solar technology through innovations in materials, design, and manufacturing processes. Energy storage solutions are crucial for storing surplus energy during peak sunlight hours and low-sunlight periods. Infrastructural limitations include grid integration and compatibility, requiring adjustments to grid management and distribution systems. Capacity building is essential for the successful adoption of solar technology, and training programs and knowledge dissemination are crucial for fostering a skilled workforce [99]. By addressing these challenges, stakeholders can work together to realize solar technology's potential, transforming energy landscapes and catalyzing positive change on a global scale.

4. Application of solar energy

Solar energy is a versatile energy source used in various sectors, including extreme environments, residential settings, transportation, industrial applications, automation, and agriculture. It empowers communities, reduces greenhouse gas emissions, and enhances energy efficiency in industries. Solar-powered technologies like water heaters, air conditioning systems, and automation in factories contribute to cleaner practices and sustainable farming.

Solar technology adoption rates vary by country, influenced by factors such as government incentives, technological advancements, and public awareness. Germany is a leader in solar energy adoption. Its aggressive renewable energy policies, including feed-in tariffs and subsidies, have driven widespread adoption. As of 2021, solar energy accounted for around 10% of Germany's total electricity generation. Australia has abundant sunshine, making it well-suited for solar energy. The country has experienced rapid growth in solar installations, both residential and commercial. As of 2021, solar energy accounted for over 20% of Australia's total electricity generation capacity. Japan has heavily invested in solar energy following the Fukushima nuclear disaster in 2011. The government introduced generous incentives for solar installations, leading to significant growth. As of 2021, solar energy accounted for about 7% of Japan's total electricity generation. The United States has seen substantial growth in solar energy adoption in recent years. Various federal and state incentives, along with falling solar panel prices, have contributed to this growth. As of 2021, solar

energy accounted for around 3% of total electricity generation in the U.S., with higher penetration rates in certain states like California and Hawaii. The Netherlands has been actively promoting solar energy as part of its renewable energy transition. Despite its relatively smaller size and less sunshine compared to other countries, solar adoption has been increasing steadily. As of 2021, solar energy accounted for approximately 5% of the Netherlands' total electricity generation. These examples demonstrate the varying levels of solar technology diffusion in advanced countries, with some achieving significant penetration into their energy mix.

4.1. Extreme environmental condition

Environmental extremes, such as pH of 2 or 11, temperature of 20 °C or 113 °C, saturating salt concentrations, intense radiation, and 200 bars of pressure, among others, are characteristics of habitats that fall outside the range where environmental conditions are most conducive to human growth [100,101]. Solar energy plays a crucial role in remote environments, providing essential services and overcoming challenges. It powers critical infrastructure, facilitates communication systems, and illuminates clean water access. Solar microgrids, made up of solar panels and energy storage systems, provide electricity to remote communities, lighting homes, schools, and clinics. Solar-powered communication systems ensure seamless connectivity, while solar-powered water purification units treat contaminated water sources, ensuring access to potable water. Solar energy also supports healthcare services, lighting clinics and facilities, refrigerating vaccines, and powering medical equipment [102,103]. Solar energy also enables educational empowerment by providing well-lit learning environments, extending study hours, and fostering literacy. Solar energy's minimal impact on the environment safeguards biodiversity, ensuring progress does not compromise nature's harmony. In extreme environments, solar power is a beacon of hope, demonstrating human ingenuity, resilience, and a shared commitment to a brighter future.

4.2. Electricity generation (power supply) to homes

Three-quarters of the Sub-Saharan African population lacks access to power. According to the IEA's World Energy Outlook 2020, there were more than 590 million people without access to electricity [104]. Solar energy is revolutionizing residential electricity generation by transforming rooftops into energy producers. This decentralized approach shifts the paradigm from passive energy consumption to active energy production, empowering homeowners to become energy producers. Solar-powered homes can generate electricity during daylight hours, fulfilling immediate energy needs and often exceeding them. Excess energy can be stored in batteries or fed back into the grid, enabling homeowners to draw from these reserves during nighttime or cloudy periods. Solar energy also offers financial benefits, such as reduced energy bills and reduced energy costs [105,106]. Solar-powered homes also contribute to environmental stewardship by reducing reliance on fossil fuels and fostering a cleaner, greener environment for future generations. Solar-powered homes also demonstrate resilience in the face of energy disruptions, enhancing household preparedness and community resilience.

4.3. Transportation

Solar energy is revolutionizing transportation by transforming high-speed trains and electric vehicles into sustainable options. Solar panels power trains, reducing carbon footprints and aligning with sustainability goals. Electric vehicles (EVs) are also redefining charging landscapes, enhancing energy independence and resilience. Solar-powered transportation influences public perception and behavior, thus driving holistic development and progress in regions facing unique challenges.

4.3.1. High-speed train

Photovoltaic panels near or on rail tracks can provide enough electricity to start a traction current that will be sent to the grid, which is how solar-powered trains are typically propelled. These technologies could offer networks that presently depend significantly on grids several economic advantages. It is becoming more difficult to produce electricity from renewable sources to power the railways due to a rising lack of funding and the fact that grids are rapidly filling.

Solar energy is being integrated into high-speed trains to provide power, reduce carbon emissions, and enhance energy efficiency. Solar panels are strategically placed along rail lines, capturing sunlight and converting it into electricity. Solar-powered trains offer a cleaner, more environmentally friendly mode of transportation, aligning with global climate goals. They also enhance energy efficiency by harnessing sunlight directly from their pathways, reducing the strain on conventional energy supply systems [107,108]. This convergence of solar energy and train infrastructure exemplifies innovation and the adaptability of solar energy across various sectors. Solar-powered trains represent a sustainable pathway forward for modern transportation, aligning with global efforts to combat climate change, mitigate air pollution, and foster sustainable mobility.

4.3.2. Electric vehicles

Solar energy is being integrated into electric vehicles (EVs) and it is transforming the automotive industry [109,110]. Solar panels are strategically placed on the vehicle's surface to capture sunlight and convert it into electricity, increasing the vehicle's overall driving range. This extends driving ranges, reducing the need for frequent charging stops and enhancing the convenience of EV ownership. Solar-powered EVs also have the potential to reduce the frequency of charging, enhancing energy autonomy and fostering a more sustainable driving experience. The integration of solar energy into EVs represents technological innovation in the automotive sector, promoting a cultural shift towards sustainable transportation practices. The solar-powered revolution is not limited to vehicles but resonates with broader challenges and opportunities in regions striving for comprehensive development and progress [111,112].

4.4. Robots and other factory equipment

Solar energy is revolutionizing the industrial sector and transforming the way factories operate. By integrating solar panels into machines and robots, these machines can generate electricity, reducing carbon emissions and minimizing energy costs. This shift aligns with the sustainability goals of modern manufacturing. Solar-powered equipment also offers economic benefits, as it draws energy from the sun, reducing dependence on conventional energy grids. This demonstrates the financial viability of sustainable manufacturing practices. Solar-powered industrial equipment also embodies the ethos of eco-friendly operations, setting an example for other industries. The innovation is not just a shift in power sources, it is a testament to the adaptability of solar energy across diverse sectors [113]. The adoption of solar-powered industrial equipment has ripple effects beyond factory walls, highlighting the manufacturing sector's role in global sustainability goals.

5. Challenges and opportunities of solar energy in the Global South

The Global South has the potential to transform energy access, livelihoods, and sustainable development through solar energy. However, challenges include technological adaptation, financial barriers, infrastructure limitations, and geographical variation [114]. A unified effort involving governments, communities, industries, and international organizations can overcome these obstacles and harness solar energy's potential for sustainable development.

5.1. Challenges and policies

5.1.1. Challenges

The Global South faces numerous challenges in implementing solar technology. The challenges include limited awareness, inadequate infrastructure, and financial constraints. All these hinder its widespread adoption due to a complex interplay of factors that impede its transformative potential.

Firstly, the Global South faces a significant challenge in promoting solar technology adoption due to limited awareness and knowledge disparities [115]. Solar energy's benefits include reliability, renewable power, reduced environmental impact, and the potential to alleviate energy poverty. This ignorance perpetuates reliance on conventional energy sources, which are often unreliable, expensive, and environmentally harmful. To bridge this knowledge gap, a collaborative effort between governments, NGOs, and local community organizations is needed. Comprehensive awareness campaigns should be crafted, utilizing diverse communication channels to reach communities beyond traditional information streams. Success stories of communities using solar energy can inspire and highlight the economic benefits, and broader impact on education, healthcare, and overall quality of life. Solar technology also offers potential for income generation through solar-based enterprises, driving self-sufficiency and resilience [116]. Accurate information dissemination through workshops, community engagement initiatives, and educational programs can empower individuals with knowledge and enable informed choices.

Secondly, the lack of adequate infrastructure hinders the adoption of solar technology in the Global South [110,117]. Vital components like energy storage solutions, efficient grid integration mechanisms, and maintenance networks are often lacking in regions with high solar power demand. To overcome these obstacles, robust investments are needed to modernize and strengthen grid infrastructure, ensuring solar energy is distributed effectively to communities. Investing in advanced energy storage technologies can help ensure a continuous power supply, especially in regions with irregular sunlight. Establishing robust maintenance networks, training local technicians, and fostering a culture of sustainability are essential for the longevity and effectiveness of solar-powered systems [118–120]. Collaboration between governments, international organizations, and the private sector is crucial for infrastructure overhaul. Governments should prioritize investment in energy infrastructure, while international organizations can offer technical expertise, financial support, and knowledge sharing to guide modernization. The private sector can also drive innovation and solutions to infrastructure barriers, introducing innovations that cater to the specific needs of the Global South.

Thirdly, financial constraints and economic realities pose significant challenges to solar technology adoption in the Global South [121]. High upfront costs, limited resources, and the absence of accessible financing options are major barriers to solar adoption. Financial accessibility is crucial for individuals and communities to overcome these barriers and embrace solar solutions. Government incentives, such as subsidies, grants, and tax benefits, can make clean energy more affordable and encourage individuals and businesses to transition to solar power. Microfinance institutions can revolutionize solar adoption by tailoring financial solutions to local contexts and income levels, providing accessible avenues for investment. Public-private partnerships can also spark innovative financing mechanisms that reduce upfront investments and stimulate economic growth. By bridging income disparities, governments, financial institutions, and private entities must work together to create a financial landscape where solar adoption becomes an accessible reality for all. With these, communities in the Global South can transcend financial barriers and forge a future where solar energy empowers individuals, uplifts communities, and paves the way for sustainable progress.

The disposal of used solar panels poses a significant challenge as they contain hazardous materials such as lead, cadmium, and silicon. Improper disposal can result in environmental contamination and health risks. Developing effective recycling and waste management systems for solar panels is essential to mitigate these risks and ensure their proper end-of-life treatment. Large-scale solar panel installations can potentially lead to environmental damage, such as deforestation or habitat loss, especially if they require significant land area. While solar panels can be installed on existing infrastructure or degraded land to minimize environmental impact, careful planning and regulation are necessary to address land-use conflicts and protect sensitive ecosystems. Ensuring the quality and safety of solar panels sold in the market is crucial for preventing performance issues, reliability problems, and safety

hazards. Quality regulation enforcement, particularly in the Global South where oversight may be limited, presents challenges such as counterfeit products, substandard manufacturing practices, and inadequate testing facilities. Strengthening regulatory frameworks, implementing standards and certification programs, and enhancing market surveillance are essential for improving the quality control of solar panels. Solar panels must be suitable for local environmental conditions, especially in regions with extreme temperatures, high humidity, or frequent dust storms. For example, in northern Nigeria, solar panels must withstand high temperatures and sand dust from the Sahara Desert. Ensuring the durability, resilience, and performance of solar panels in diverse environmental contexts requires rigorous testing, product design modifications, and technology adaptation to local conditions. Collaboration between manufacturers, researchers, and local stakeholders is essential to address these challenges and ensure the effectiveness and longevity of solar panel installations in the Global South.

Problems with land acquisition have a major impact on the Global South's acceptance of solar power, impeding the development of large-scale solar projects and the proliferation of renewable energy. Significant barriers include the scarcity of adequate land, competition from other land uses like urbanization and agriculture, and problems with ownership and land tenure. Uncertainty about land titles, conflicting claims, and disagreements can complicate land acquisition procedures, adding time and risk to investments. The difficulties are further compounded by community opposition stemming from worries about disruptions to livelihoods, environmental effects, and cultural heritage, in addition to complex regulations and bureaucratic roadblocks. Overcoming these challenges calls for an all-encompassing strategy including several parties. Governments must first speed permits and lessen administrative hurdles for developers by streamlining regulatory frameworks, streamlining permitting processes, and establishing clear rules. Processes for acquiring land can also be facilitated by increasing agency coordination. Secondly, it is imperative to cultivate significant involvement and dialogue with nearby communities. To win support for solar projects, developers need to take care of community issues, maintain transparency, and set up benefit-sharing arrangements. Furthermore, in order to minimize negative effects and guarantee project sustainability, comprehensive environmental and social impact evaluations and the implementation of mitigation strategies are crucial. Third, minimizing conflicts and facilitating land acquisition can be achieved by supporting sustainable land-use planning techniques and locating appropriate locations for solar installations. To prevent rivalry with conservation areas and agriculture, governments should give priority to developing solar energy on damaged or marginalized regions. Incentives for solar development, such as land-use incentives, tax rebates, and subsidies, can also increase a project's economic viability and investor appeal. Governments, developers, civil society organizations, and local communities can work together in cooperative partnerships to effectively address land acquisition difficulties by pooling resources and expertise. To put it briefly, resolving conflicts between competing land uses, attending to social and environmental issues, streamlining regulatory procedures, and promoting inclusive decision-making processes are all necessary to overcome land acquisition obstacles. Stakeholders may fully utilize solar energy to support climate change mitigation, energy access, and sustainable development in the Global South by tackling these obstacles.

Collaboration between governments, international organizations, local communities, and private sector entities is crucial for overcoming these obstacles. Raising awareness, developing tailored infrastructure, and implementing innovative financing solutions can lead to a solar-powered future that transcends boundaries and promotes sustainable development.

5.1.2. Policies and drivers

Adoption of solar energy technologies is greatly aided by policies that promote climate resilience, particularly in the Global South's most vulnerable areas where the effects of climate change are most severe. By making energy systems and infrastructure more resilient to hazards associated with climate change, these policies hope to increase the use of renewable energy sources like solar power. Climate resilience policies facilitate the widespread deployment of solar energy by combining financial incentives, regulatory frameworks, support for research and development, capacity building activities, and planning efforts for adaptation.

Financial incentives—such as tax credits, grants, subsidies, and low-interest loans—are essential in lowering the initial costs of solar adoption. For homes, businesses, and governments, solar energy is now more financially feasible thanks to these incentives. Due to these advantages, solar energy is now more economically feasible for homes, companies, and governments, which promotes investment in solar installations and expands the market. Solar energy developers and investors benefit from the clarity, predictability, and assurance that come with the regulatory frameworks put in place under climatic resilience policies. Regulatory tools that encourage solar integration into the energy mix and ease grid integration include renewable energy objectives, feed-in tariffs, net metering plans, and interconnection regulations. These tools make it possible for solar electricity to be seamlessly integrated into current energy systems. Policies promoting climate resilience also encourage the advancement of solar energy technology research, development, and innovation. Governments may accelerate technological developments, improve efficiency, lower costs, and improve the performance and dependability of solar energy systems by allocating funds for research and development. This increases the marketability and competitiveness of solar electricity, hastening its adoption and implementation. Policies promoting climatic resilience must also include capacity building and technical support initiatives. By removing adoption hurdles and guaranteeing the sustainable development of solar energy infrastructure, these programs improve local knowledge and proficiency in solar energy deployment, operation, and maintenance. In addition, regulations incorporating adaptation planning and risk management techniques aid in addressing the possible effects of climate change on solar energy infrastructure. Policymakers can guarantee the dependability and longevity of solar systems in the face of climatic variability and change by identifying vulnerabilities, evaluating risks, and putting policies in place to improve resilience to extreme weather events. Climate resilience policies address technical, financial, regulatory, capacity-building, and risk management issues to offer a framework that encourages the use of solar energy. Governments may expedite the shift to a low-carbon, sustainable energy future fueled by solar and other renewable energy sources by including climate resilience concerns into energy policy and planning procedures.

5.2. Opportunities

Solar technology adoption in the Global South presents opportunities for sustainable development, economic growth, and employment, fostering economic growth, and promoting environmental stewardship, despite challenges in adoption. Solar energy is a beacon of hope in the Global South that could offer a transformative opportunity to bridge energy gaps. It can be used to provide reliable and sustainable energy access to communities, unlocking energy self-sufficiency and empowering them to harness the sun's energy. Off-grid areas often cut off from progress, can benefit from solar panels, extending their productive hours, fostering education, and nurturing healthcare facilities. Solar technology also catalyzes socio-economic activities, allowing communities to establish businesses, power schools, and run clinics, promoting economic growth and social advancement. Solar energy transcends geographical divides, democratizing energy access, and ensuring that every corner of the Global South experiences the life-changing benefits of electricity. This unity erases disparities, catalyzes progress, and fosters a sense of shared empowerment. Solar energy is not just about illuminating homes; it's about illuminating lives and pathways to progress [122]. The transformative potential of solar energy lies not just in the electrons it generates, but in the lives it illuminates. Governments, communities, and stakeholders stand at the threshold of an energy revolution, where solar technology serves as a beacon of progress, guiding the Global South towards empowerment, sustainability, and shared prosperity. Embracing the opportunity of one solar panel at a time will lead to not just the lighting up of homes, but the lighting up of lives.

Solar energy is a powerful conduit for sustainable development and green growth in the Global South. It aligns with global sustainability goals, reducing carbon emissions and mitigating climate change. By harnessing the sun's power, communities in the Global South can contribute to a more sustainable future. Solar-powered solutions can replace fossil fuel dependency, paving a path towards cleaner air and a healthier environment. Solar energy catalyzes holistic development across key sectors, such as agriculture, healthcare, and education. Solar-powered irrigation systems enhance crop productivity, while solar-powered clinics and medical equipment power healthier lives. In education, solar technology extends study hours and equips schools with essential resources. Industry-powered factories and businesses can embody green growth to achieve economic advancement while adhering to stringent environmental standards. With the adoption of solar energy, industries can enhance their competitiveness, reduce operational costs, and leave a lighter environmental footprint.

The solar energy revolution provides a transformative potential for employment generation and economic resilience in the Global South. The solar industry offers a spectrum of job opportunities, from manufacturing solar panels to installing systems, maintaining equipment, and offering technical support. This decentralized employment generation ensures that economic benefits are shared across communities, driving inclusive growth that transcends geographic boundaries. The solar sector addresses unemployment challenges by providing avenues for individuals to secure gainful employment and support their families. The sector can also empower communities with economic stability and dignity. Skill development and capacity-building are essential in the solar sector. Individuals in roles spanning technology, engineering, installation, and maintenance acquire expertise in a rapidly growing industry, empowering them with skills that shape their future. Economic resilience is woven into the fabric of the solar energy revolution, as the diversification of economic activities reduces vulnerability to economic shocks. Communities with a robust solar industry presence are better equipped to weather uncertainties, as the sector provides a buffer against downturns in other industries. The solar energy revolution contributes to overall prosperity by feeding into improved living standards, enhanced education, and better healthcare. As the Global South seeks to embrace solar technology, it embarks on a journey where the radiance of the sun is mirrored in the radiance of empowered lives.

There is a huge opportunity as studies shows willingness-to-pay for solar technologies in the Global South. Recent studies on demand and willingness-to-pay for solar technologies in the Global South provide valuable insights into consumer preferences, economic factors, and policy implications for renewable energy adoption. Best et al. [123] conducted research on consumer preferences and willingness-to-pay for solar home systems in Sub-Saharan Africa, highlighting the importance of affordability, reliability, and financing options in driving adoption. Sievert & Steinbuks [124] explored the determinants of demand for solar products in rural areas of developing countries, emphasizing the role of income, education, and access to financing in shaping consumer choices. Bonan et al. [125] analyzed the impact of policy interventions and market dynamics on the adoption of solar technologies in South Asia, providing insights into the effectiveness of subsidies, incentives, and regulatory frameworks in promoting renewable energy uptake. Meriggi et al. [126] investigated the factors influencing the diffusion of solar water pumps in agricultural communities, focusing on technical, economic, and social barriers to adoption and scalability. Abdul-Salam & Phimister [127] examined the role of community-based initiatives and social networks in promoting solar energy adoption in rural areas, highlighting the importance of community engagement and trust in driving behavioral change. These studies contribute to our understanding of the demand-side dynamics of solar technology adoption in the Global South, informing policymakers, investors, and practitioners on strategies to accelerate the transition to clean and sustainable energy solutions.

Solar energy is not only a source of power but also a path of environmental stewardship and community empowerment. Communities in the Global South can reduce their carbon footprint, signifying a commitment to cleaner air, healthier ecosystems, and a more sustainable planet by harnessing the sun's energy. Solar energy's ripple effect extends beyond power generation, gently touching and preserving local ecosystems. By choosing solar technology, communities mitigate the environmental damage caused by conventional energy sources, empowering them to safeguard the natural resources upon which their livelihoods depend. Community-level solar projects empower individuals to take ownership of their energy production, cultivating a culture of self-reliance and environmental responsibility. This fosters a connection with the environment, a drive for sustainable living, and a commitment to future generations. As the Global South embarks on a journey of solar empowerment, it forges a legacy deeply rooted in environmental stewardship and community empowerment.

The potential returns to solar power in agriculture hinge on various factors such as farming systems, relative costs of alternative substitutes, technology adoption, environmental considerations, and access to finance. Takeshima et al. [128] stress the importance of household-level typologies and simulation-based assessments for evaluating mechanization technologies, including solar power. Factors like energy demands, labor costs, and technology compatibility influence the economic feasibility of solar power. Additionally, environmental benefits and government incentives can enhance returns[129,130]. A holistic approach considering these aspects is crucial for accurately assessing the viability and economic benefits of solar power investments in agriculture.

6. Conclusion

Solar energy is a promising solution for the Global South, offering immense potential to address challenges such as lack of reliable access to electricity, insufficient water resources, limited industrial growth, and food insecurity. It can empower communities with enhanced healthcare, education, and sustainable agriculture. However, this potential cannot be realized in isolation; collaboration on a grand scale is necessary. Governments must spearhead supportive policy frameworks, offering incentives and regulatory clarity. Organizations, both local and international, could also play a vital role in delivering technological expertise, financing solutions, and capacity-building initiatives. Communities must embrace the opportunity and drive local adoption. Barriers such as lack of awareness, inadequate infrastructure, and financial constraints loom large but also harbor growth opportunities. Inadequate infrastructure can be addressed through strategic investments that nurture resilient energy systems. Also, financial constraints can be eased through innovative financing models that democratize access to solar technology. The Global South's journey towards harnessing solar energy is a collective pursuit of progress, transforming challenges into stepping stones and opportunities into pathways. With the illuminating possibilities of solar energy, a bright and sustainable future is on the horizon that powers progress and fosters resilience. The challenges may be formidable, but they are met with an even greater resolve to create change. The opportunities of these policies are boundless, waiting to be seized by individuals, communities, and societies driven by the shared vision of a brighter tomorrow. As stakeholders and stewards of progress, it is up to us to paint the story of a solar-powered future, radiating hope, progress, and a legacy of sustainable prosperity for generations to come.

Declaration

The authors declare that there is no conflict of interest arising from this work.

CRediT authorship contribution statement

Kingsley Ukoba: Writing – original draft, Data curation. **Kelvin O. Yoro:** Writing – review & editing, Conceptualization. **Oreva oghene Eterigho-Ikelegbe:** Data curation. **Chinedu Ibegbulam:** Data curation. **Tien-Chien Jen:** Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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